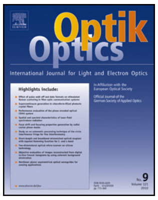
Optik 164 (2018) 679–685

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Original research article

Birefringence detection of a gradient-index lens based on astigmatic transformation of a Bessel beam

S.N. Khonina[a,b,*], S.V. Karpeev[a,b], V.D. Paranin[b]

[a] *Image Processing Systems Institute – Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of Russian Academy of Sciences, Molodogvardeyskaya St. 151, Samara, 443001, Russia*
[b] *Samara National Research University, Moskovskoe Shosse 34, Samara, Russia*

ARTICLE INFO

Article history:
Received 3 October 2017
Accepted 22 March 2018

Keywords:
Bessel beam
Birefringence
Optical path difference
Astigmatic transformation
Quarter-pitch parabolic gradient-index lens

ABSTRACT

A method is proposed for detecting birefringence of mechanically free parabolic gradient-index lenses based on the astigmatic transformation of the zero-order Bessel beam. Numerical simulation shows a clearly visible distortion of the intensity structure in the propagation of scalable astigmatic Bessel beams. The degree of astigmatism can be determined from the intensity distribution of the distorted beam. Similar patterns are also obtained in an experimental study of the passage of a Bessel beam through a quarter-pitch gradient-index lens, which indicates the presence of birefringence of the lens material. Comparison of experimental data and numerical simulation shows the possibility of measuring the optical path difference of no worse than $0.05\lambda_0$ between ordinary and extraordinary beams.

1. Introduction

One of the problems of information-measuring fiber-optic systems is the random birefringence of the constituent elements (for example, birefringence of a single-mode optical fiber due to the ellipticity of the core). Birefringence leads to an uncontrolled change in polarization of radiation, characteristics of fiber sensors, and values of measured signals. Birefringence is also inherent in gradient-index lenses due to residual mechanical stresses introduced by a dopant, which causes a reduction in the efficiency of the radiation coupling into an optical fiber due to astigmatic distortion and changes in the state of beam polarization [1]. Thus, control of birefringence is an important practical task that contributes to an increase in accuracy and reliability of transmitted information in fiber-optic and optoelectronic systems.

The study of gradient-index lenses produced by different manufacturers [2–5] showed that the optical path difference between ordinary and extraordinary rays in the central part and in the edge region is $\sim 0.01\lambda 0$, and $\sim 0.1\lambda 0$, respectively. In this case, the polarization interference method of studying birefringence [2–4] has low sensitivity. Interference methods [2,5] are more accurate; however, they are much more complicated and expensive.

The authors of Refs [6–12] proposed a new method for studying birefringence, based on the transformation of Bessel laser beams in anisotropic media. In the case of z-cut uniaxial crystals, the propagation of beams along the optical axis is accompanied by a periodic change in the order of the beam [6–9]. For x-cut crystals, typical is the astigmatic transformation of a beam propagating perpendicular to the optical axis [10,11]. It consists in the formation of a rhomboidal contour of the

---

[*] Corresponding author at: Image Processing Systems Institute – Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of Russian Academy of Sciences, Molodogvardeyskaya St. 151, Samara, 443001, Russia.
E-mail address: khonina@smr.ru (S.N. Khonina).

https://doi.org/10.1016/j.ijleo.2018.03.086

output beam, filled with local point intensity maxima. The number and intensity of these maxima are related to the degree of birefringence of the medium and, accordingly, to the resulting astigmatic difference.

Thus, the analysis of the optical properties of samples can be carried out using the intensity distribution of the beam that has passed through a sample in question, which makes it possible to perform rapid measurements with the help of standard low-cost optical components.

As shown by experimental studies [10,11], the beam parameters depend significantly on the optical properties and thickness of the anisotropic medium. The sensitivity variation of the proposed method is achieved by changing the numerical aperture of the illuminating Bessel beam. This makes Bessel beams a promising and flexible tool for studying optical media with birefringence of different types. Since the proposed method is optical and contactless, the technological purity and mechanical integrity of the samples is maintained. Thus, the method is applicable to the examination of thin films and plates, as well as soft and brittle optical materials.

The purpose of this work is a theoretical and experimental investigation of gradient-index optical lenses based on the astigmatic transformation of the zero-order Bessel beam. In the experiments, we study birefringence of a quarter-pitch gradient-index lens, which is used for coupling in/out radiation of an optical fiber.

2. Numerical study

The Bessel laser beams, due to their intensity structure, are very sensitive to wavefront asymmetry, which makes them useful for studying optical anisotropy and astigmatic beams. The changes in the intensity distribution of the propagating Bessel beam are much more noticeable and evident at lower phase distortions than for beams with uniform intensity.

In particular, a noticeable visual distortion of the beam intensity structure was observed for Bessel beams propagating perpendicularly to the axis of an anisotropic crystal [11–14], as well as passing through a cylindrical lens [15]. A similar transformation of the beam structure can be observed at an oblique incidence of a plane wave on the axicon [16–18], which, as is known, forms a Bessel beam.

To study the birefringence of gradient-index optical lenses with the help of the zero-order Bessel beam, we will use the following approach: The gradient lens is replaced by a conventional lens having a corresponding numerical aperture and the presence of birefringence in the gradient-index lens material is modeled by introducing astigmatism.

2.1. Paraxial model

First, we consider the paraxial model and use the Fresnel transform

$$G(u,v,z) = -\frac{ik}{2\pi z}\exp(ikz)\int_{-R}^{R}\int_{-R}^{R} g(x,y)\exp\left[\frac{ik}{2z}\left((x-u)^2+(y-v)^2\right)\right]\,\mathrm{d}x\,\mathrm{d}y \tag{1}$$

as the beam propagation operator, where $k = 2\pi/\lambda$ is the wave number, λ is the radiation wavelength, z is the distance from the input plane, and R is the radius of the input field.

In the input plane there is a binary phase diffraction axicon that forms a zero-order Bessel beam and is described by the complex transmission function:

$$\tau_{ax}(x,y) = \exp\left\{ i\arg\left[\cos\left(k\alpha_0\sqrt{x^2+y^2}\right)\right]\right\}, \tag{2}$$

where α_0 is the parameter corresponding to the numerical aperture of the axicon: $\alpha_0 = \lambda/d$ (d is the period of an annular lattice).

Also, in the input plane there is an astigmatic lens with a transmission function:

$$\tau_{lens}(x,y) = \exp\left\{-ik\frac{\left(x^2+\mu y^2\right)}{2f}\right\}, \tag{3}$$

where f is the focal length of the lens, and μ is the astigmatic parameter.

Thus, the input function in (1) has the form:

$$g(x,y) = \tau_{ax}(x,y)\cdot\tau_{lens}(x,y). \tag{4}$$

Table 1 shows the results of modeling the zero-order astigmatic Bessel-type beam using formulas (1)–(4) with the following parameters: $\lambda = 633$ nm, $R = 10$ mm, $\alpha_0 = 6.33\cdot10^{-4}$, and $f = 2500$ mm.

As can be seen from the results given in Table 1, in the absence of astigmatism ($\mu = 1$, the first row of Table 1), the binary axicon (2) forms a Bessel beam in front of and behind the focal region. In the focal plane (at $z = f = 2500$ mm), as is known [19], a double narrow ring is formed, the radius of which is proportional to the axicon parameter α_0. The length of the Bessel beam is directly proportional to the radius of the input field and inversely proportional to the parameter α_0. Note that the size of the light spots in the Bessel beam increases with distance from the focal plane. This fact of the transformation of an ordinary Bessel beam by a lens into a scale-expanding Bessel beam was studied in detail by Khonina et al. [20].